Optics
(in the context of PV devices)

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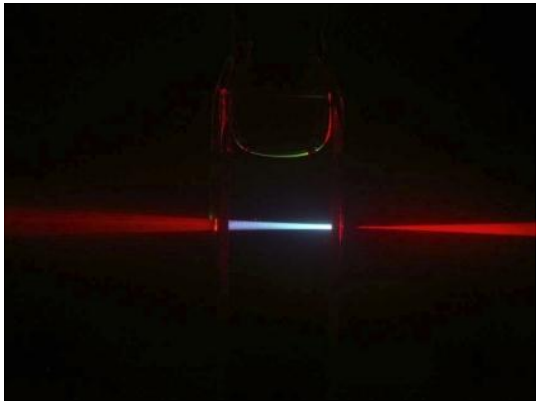


Minerva school, Nazareth, December 12th, 2011

וַיֹּאמֶר אֱלֹהִים, יְהִי אוֹר;
וַיְהִי-אוֹר.

בראשית א, ג

And God said: 'Let there be light.'
And there was light

Genesis I , 3

Outline

- A few words about light (in the context of PVs)
- "classical" electromagnetic field manipulation ('loss reduction'): anti-reflection, scattering, waveguiding
- Spectral shaping and conversion ('beating Shockley-Queisser'): upconversion, downconversion, intermediate-band cells
- Some recently revisited concepts
  - Luminescent concentrators
  - Plasmonic solar cells
  - FRET in solar cells
- Conclusion

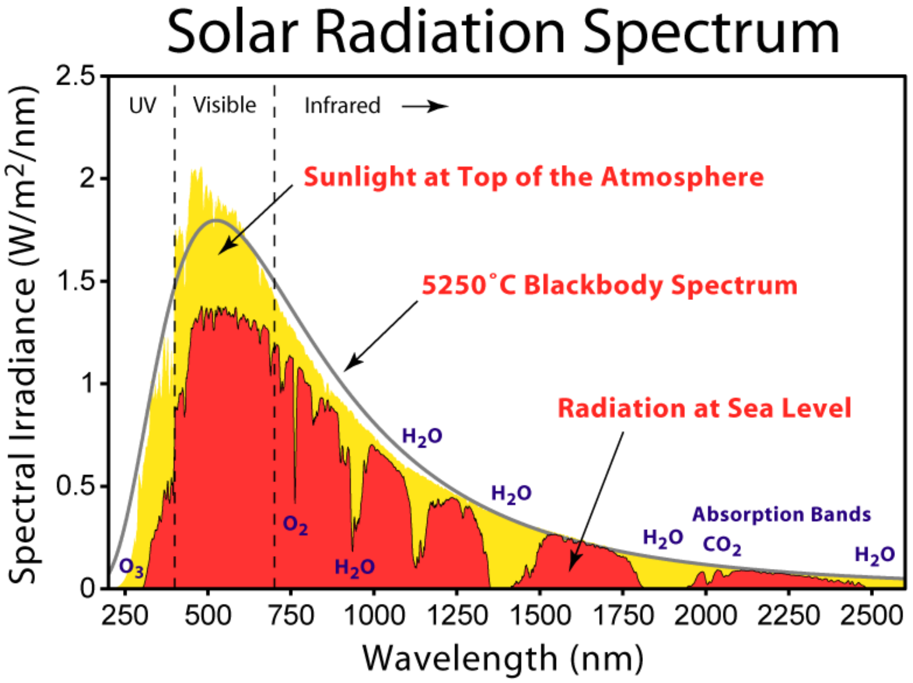
"optics"

Rough definition (for the sake of this talk):

"control or manipulation of solar radiation through light-matter interactions"

"classical" wave optics (material characterized by dielectric function)

"photons" (*) (material characterized quantized energy spactrum)



* This has nothing to do with quantum optics (light quantization)

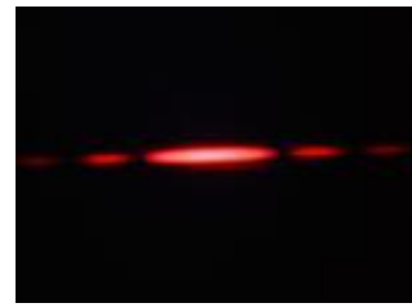
light (1)

Light is an electromagnetic field. Propagation is governed by classical wave theory (Maxwell's equations, 1861).

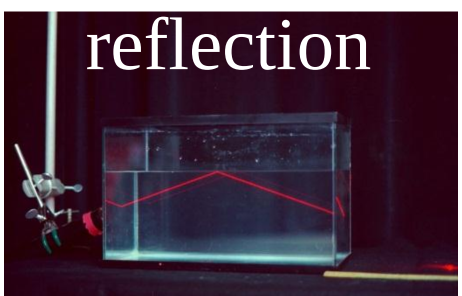
reflection

refraction

interference

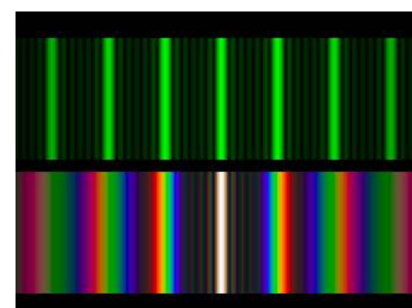


total internal reflection



scattering

diffraction

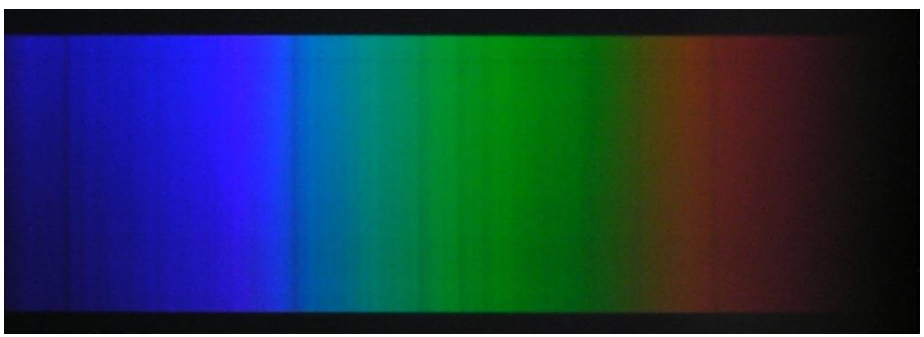


light (2)

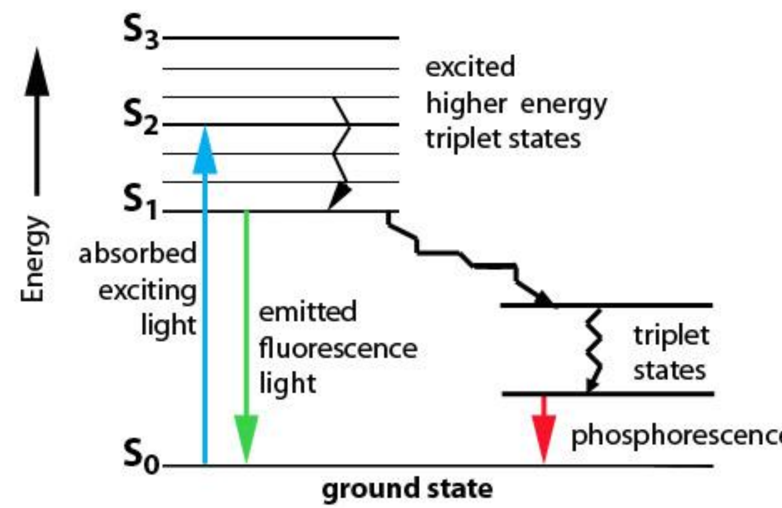
On the other hand, …

Light energy is quantized, so that color end energy are related (photoelectric effect, 1905).

$$E=h\nu$$



Discretized absorption spectra



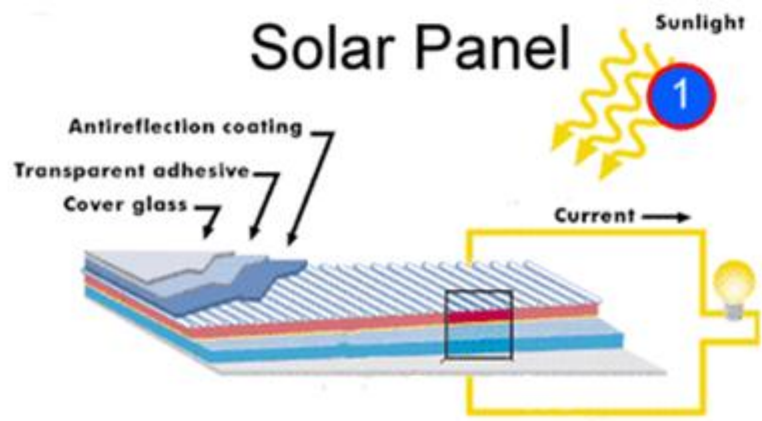
Fluorescence and phosphorescence

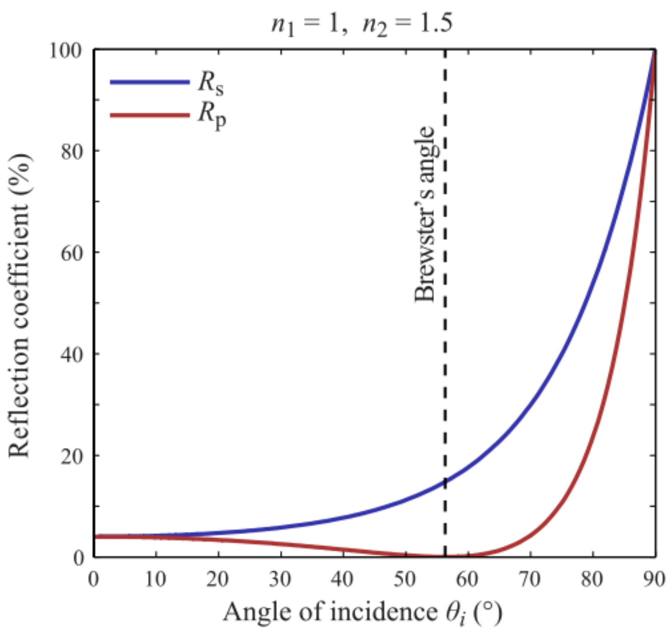
"Classical" light manipulation

Anti-reflection coating

Fresnel reflection occurs in any discontinuity of the refractive index!
At normal incidence:

$$R=[(n_2-n_1)/(n_2+n_1)]^2$$





"Classical" light manipulation

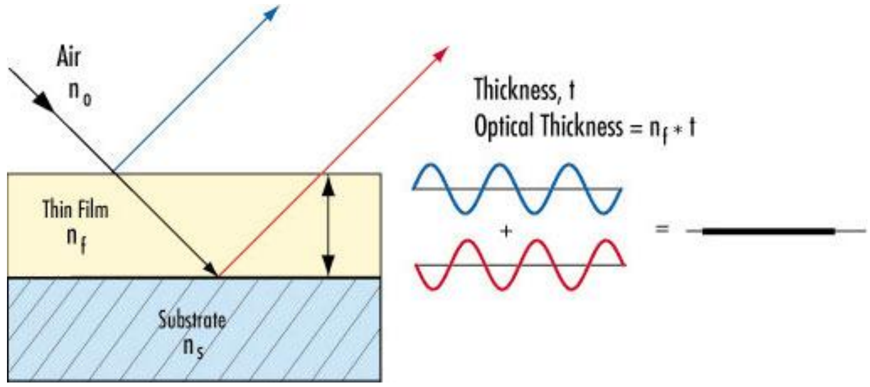
Anti-reflection coating

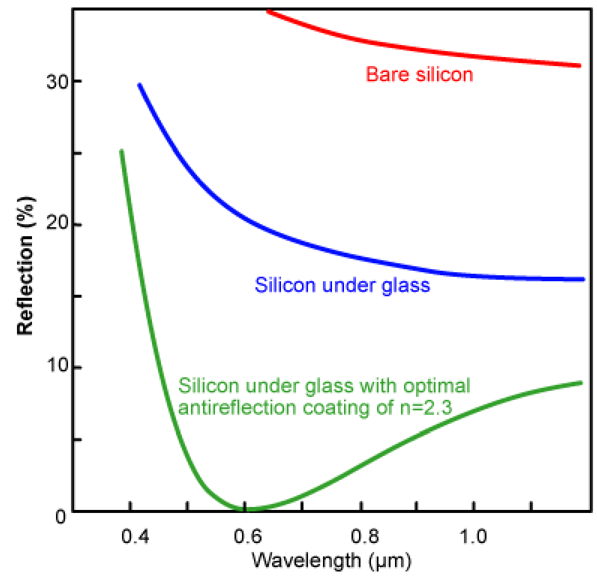
For Silicon (n~3.5-4) this is really bad news … (>30% loss)

AR coating uses wave interference for impedance matching

But …

AR coating efficiency depends:
on color …
and on angle …
multilayer stacks are very expensive …



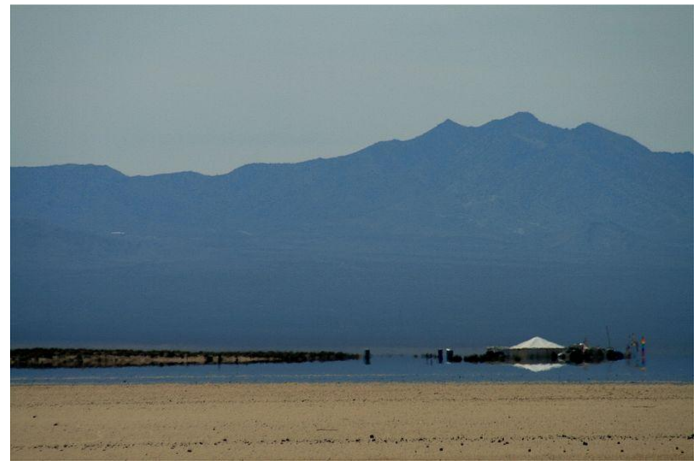


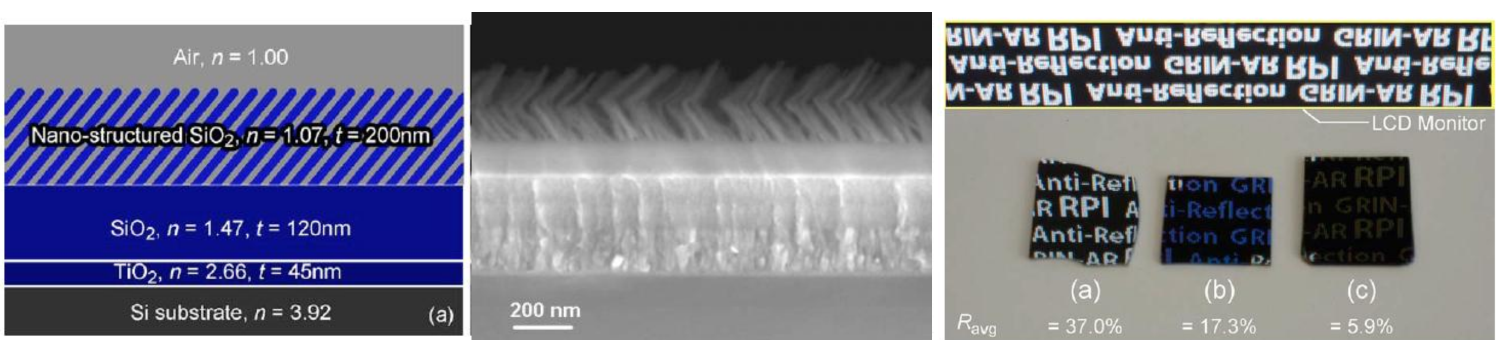
"Classical" light manipulation

Nanostructured (subwavelength) AR coatings

Can we make simple AR coating with broad acceptance angle and broad spectral performance?

Continuous change in refractive index resembles multilayer stack
Subwavelength structures – effective medium with "mixed" refractive index



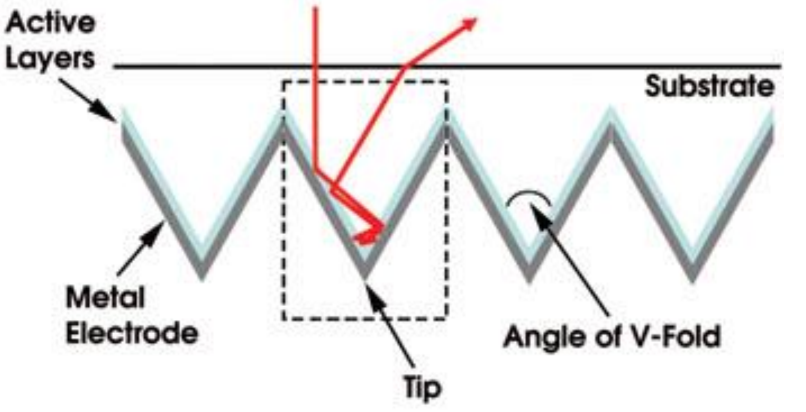


Chhajed et al., APL 93, 251108 (2008)

“Classical” light manipulation

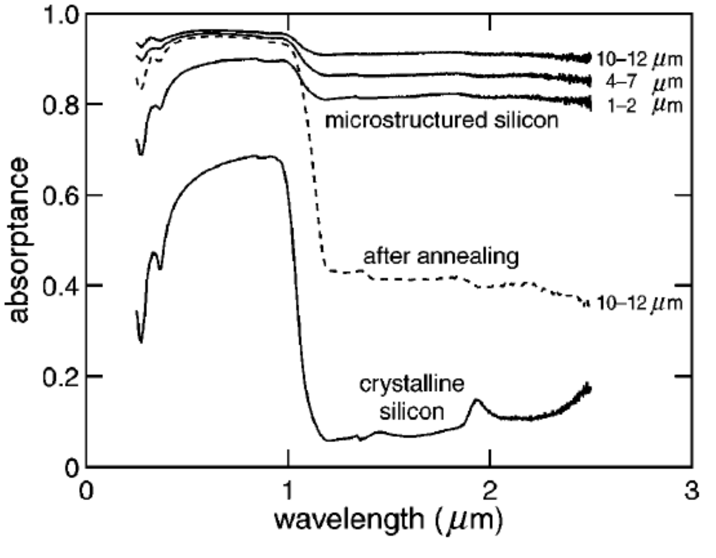
Scattering

Use of scattering makes sense since light comes mostly near normal incidence.



Thinner layers can absorb more light leading to:
Savings on materials
Less recombination loss

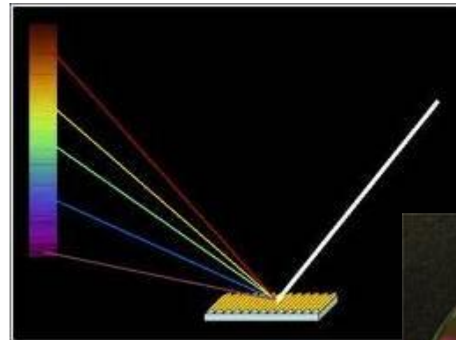
Bonus: ~1 wavelength structures also act as AR coatings



Wu et al., APL 78, 1850 (2001)

“Classical” light manipulation

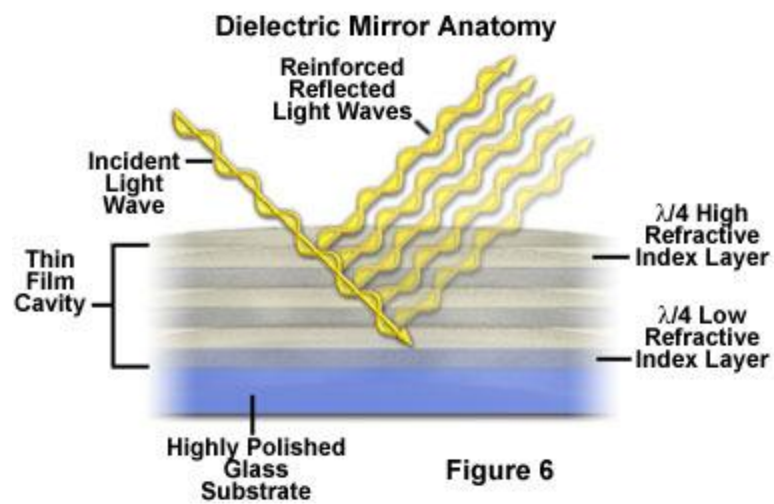
Diffraction



Gratings (more generally “photonic crystals” in 1,2 or 3 dimensions) scatter light coherently and separate colors.

These are scetterers with engineered angular scattering properties

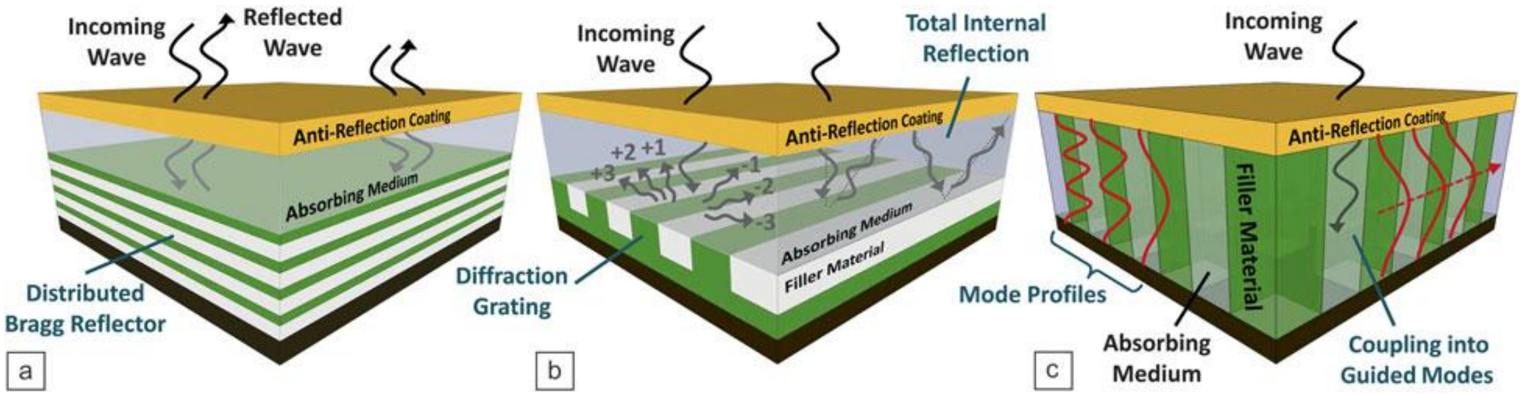
They can be used as all dielectric color and angle selective mirrors



“Classical” light manipulation

Diffraction

Periodic gratings are used in a variety of geometries …



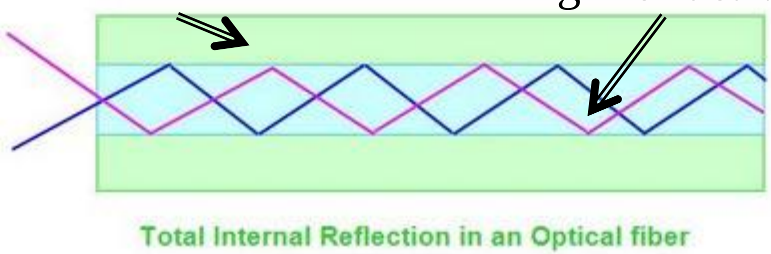
They can be thought of as providing momentum to photons perpendicular to the grating direction.

“Classical” light manipulation

Light trapping (“waveguiding”)

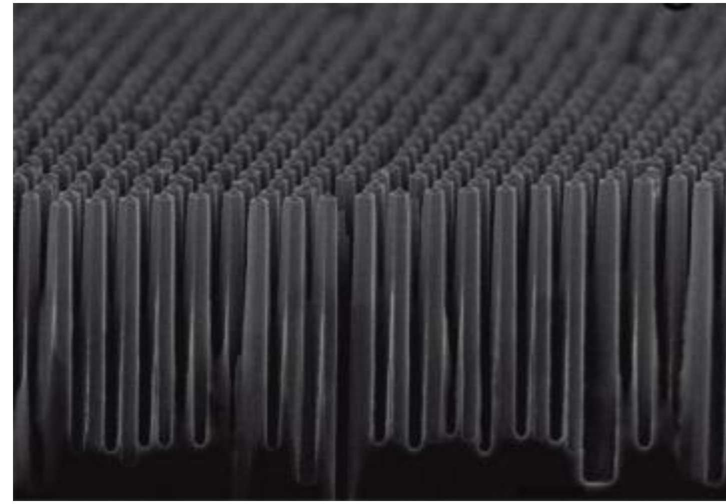
Electromegnetic fields in spatially non-uniform structures localize in high refractive index substrates.

Low refractive index   High refractive index

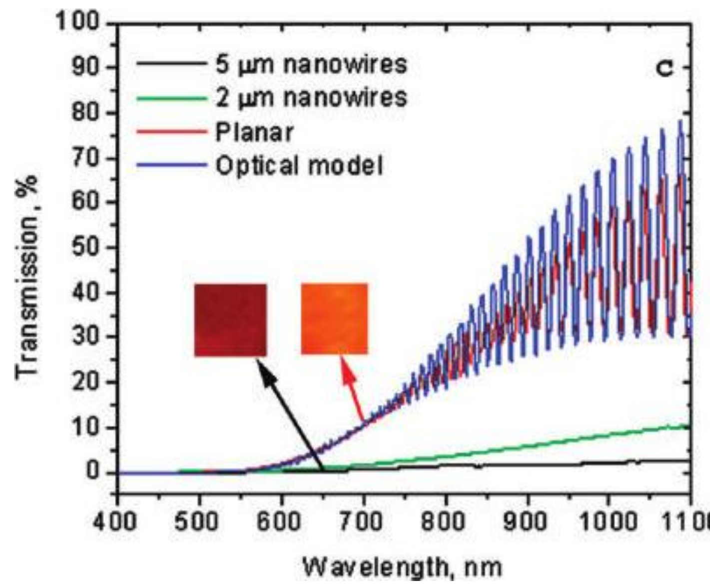


Means more absorption in less material

Garnett & Yang, Nano Lett. 10, 1082 (2010)



Si Nanowires



"Classical" light manipulation

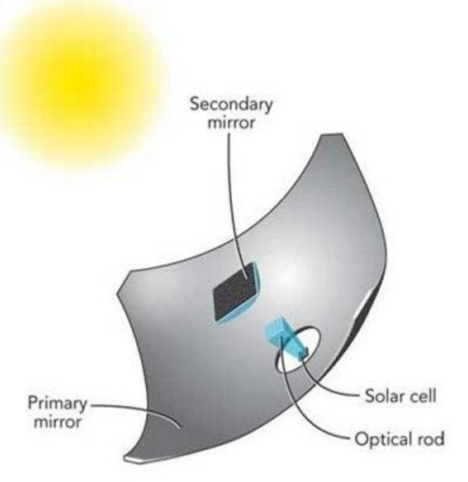
<u>Good old reflective or refractive concentration</u>

Advantages:

- Some gain in efficiency
- Can use expensive cells (tandem)
- Better chances for frequency conversion to work

Disadvantages:

- Need tracking
- Lose diffuse light

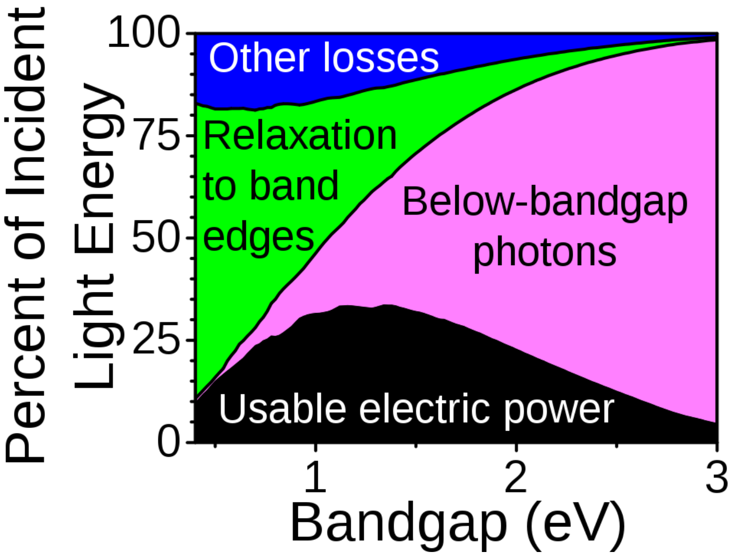


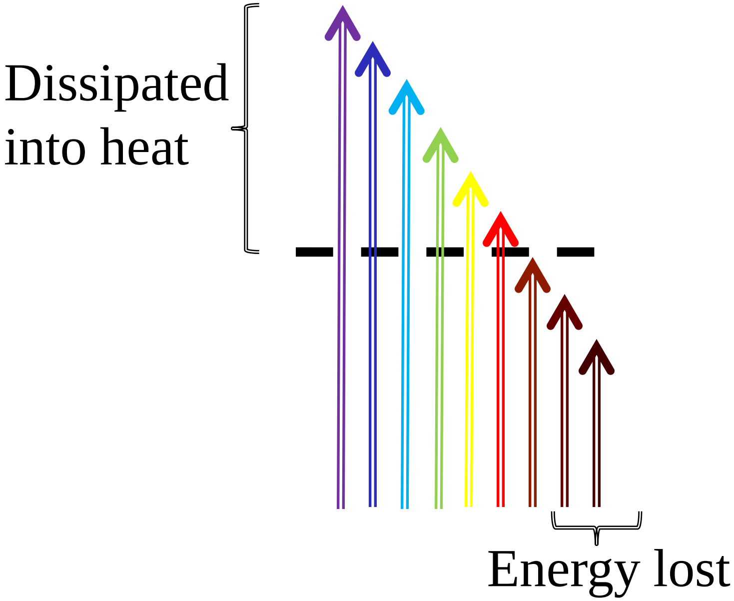
Talk by
Avi Kribus

“Nonclassical” light manipulation

<u>Alternative to tandem cells</u>

Tailoring the color of solar light to fit the band gap of a single junction solar cell

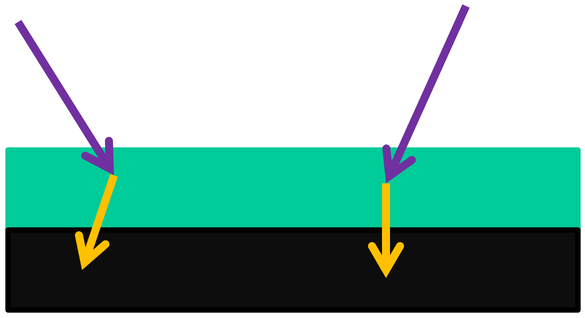




Color conversion schemes can help recapture some of the lost energy!

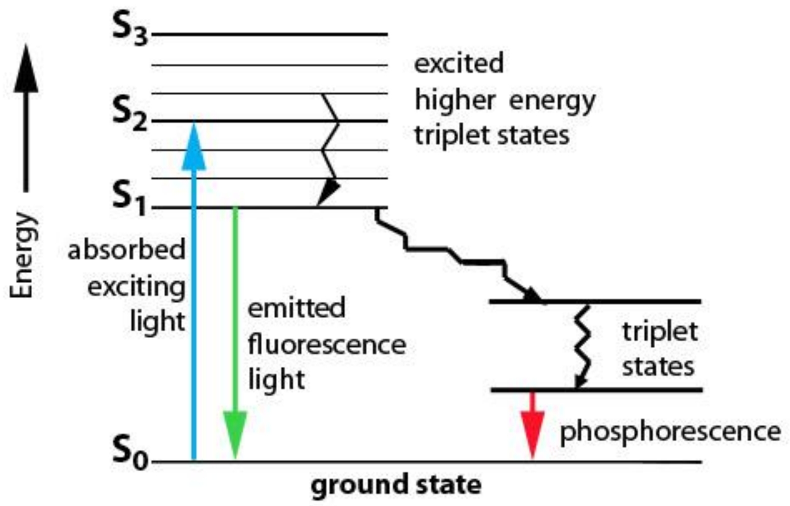
“Easy”: Spectral downshifting

Convert UV-violet photons to visible photons



Why?

- Better efficiency for visible photons
- Avoiding UV damage

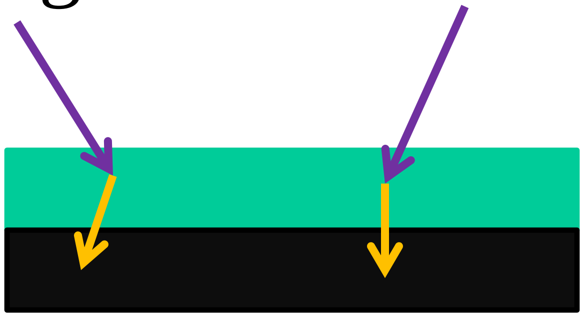


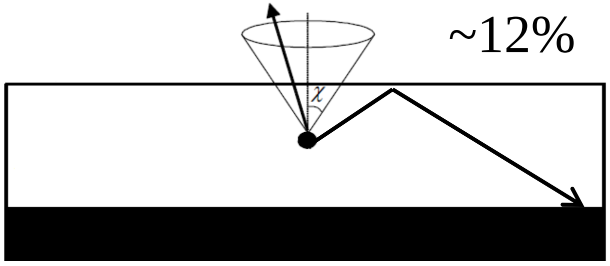
But…
No improvement over Shockley-Queisser limit!

Spectral downshifting

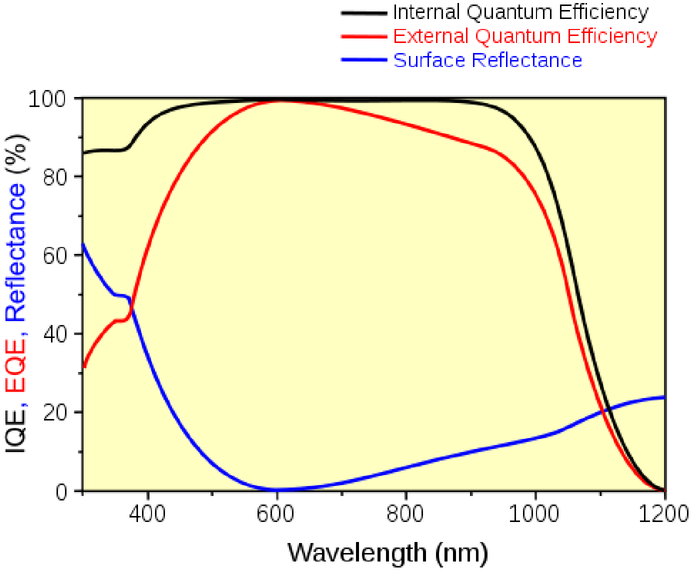
Inherent loss due to:

- Escape of fluorescence light requires poor UV performance to benefit
- Emission quantum yield

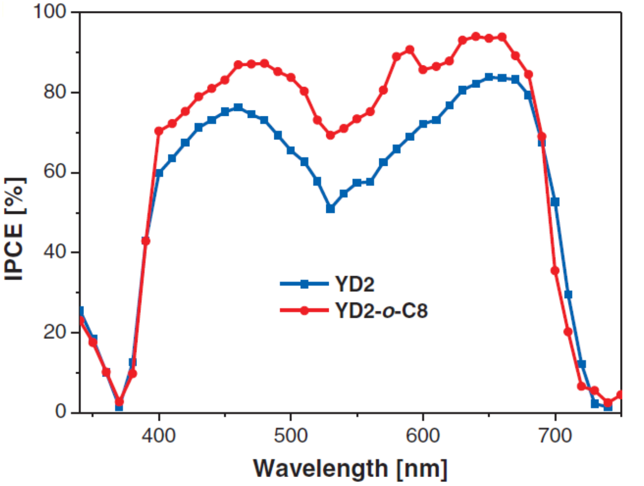




~12%



Si cell

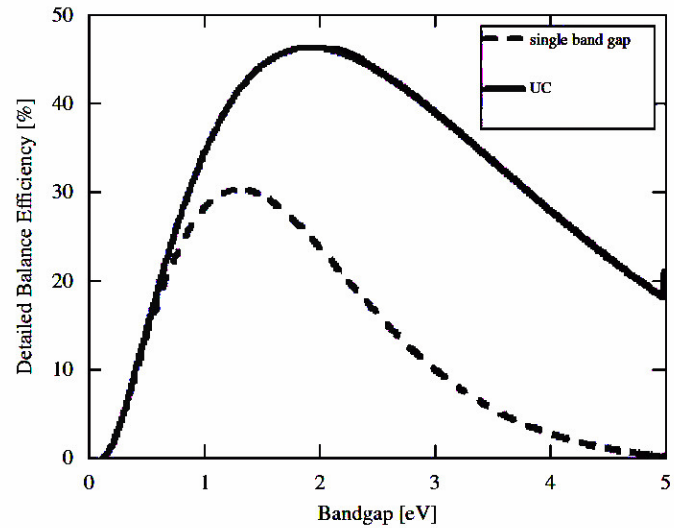


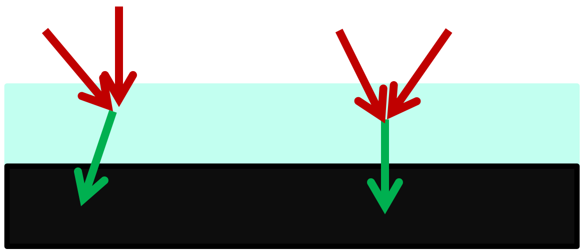
Best DSSC

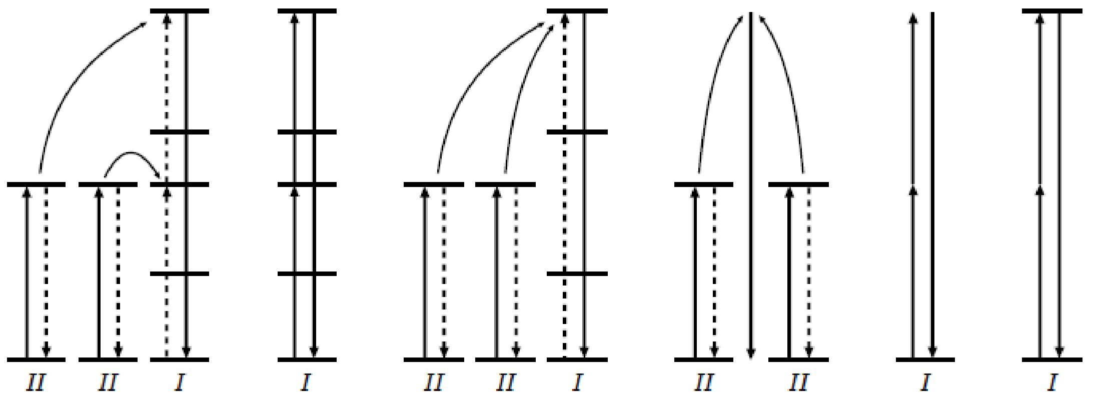
Yella et al., Science 334, 629 (2011)

"Hard": photon upconversion

"Fusing" two low-energy photons into one high-energy photon potentially improves cell performance by reducing NIR losses



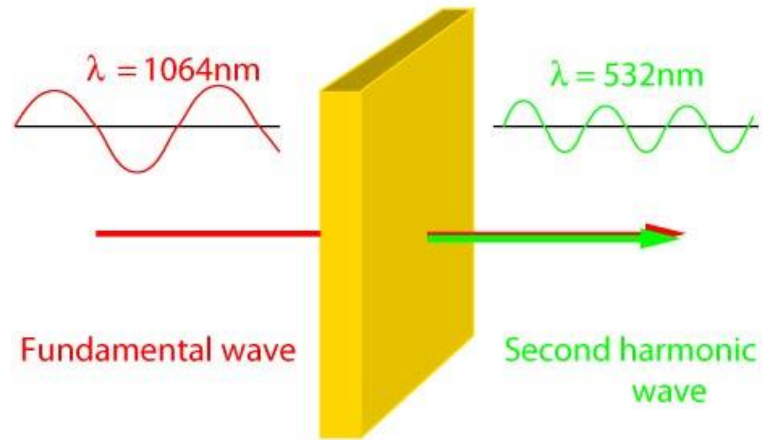




Shpaisman et al., Solar Energy Materials & Solar Cells 92, 1541 (2008) ; Aarts, PhD thesis (2009)

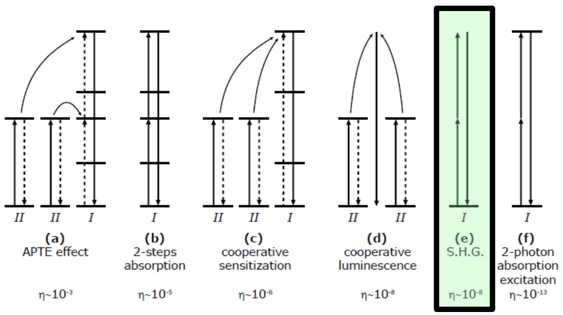
Photon upconversion

SHG: the common laser technology for color conversion.



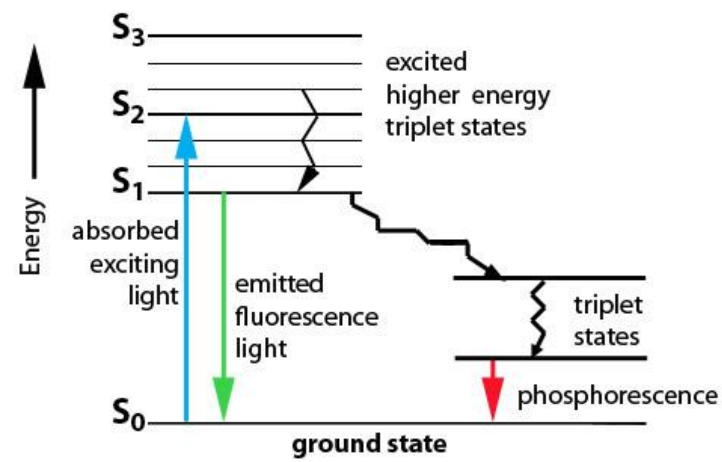
but…

It requires a peak power of ~1MW/cm^2 to be efficient. NIR solar irradiance is <<1W/cm^2, so even with focused light, it is completely impractical



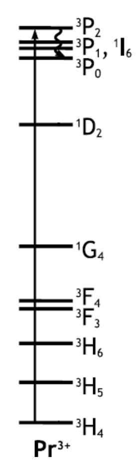
Photon upconversion

Focusing requirements will be mitigated if the system has a long–lived intermediate state.
However, relaxation back to the intermediate state should be forbidden!



Dipole forbidden transitions are usually associated with spin or parity:

Triplet states in organic molecules



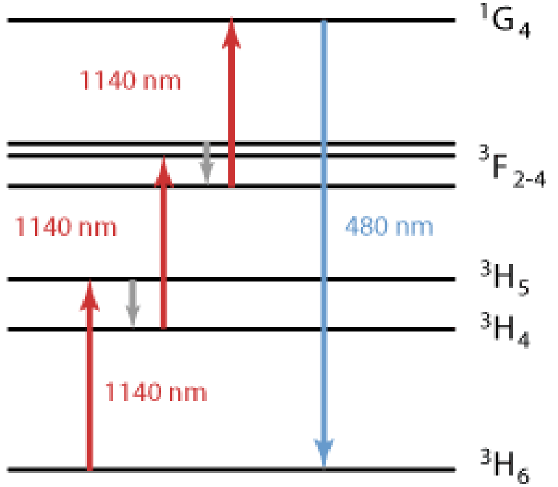
Phosphorescence in rare-earth doped glasses

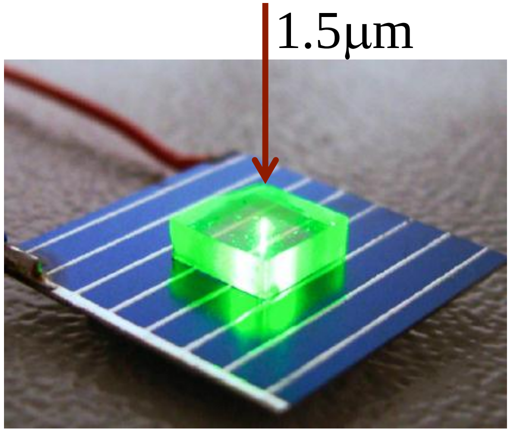
Photon upconversion

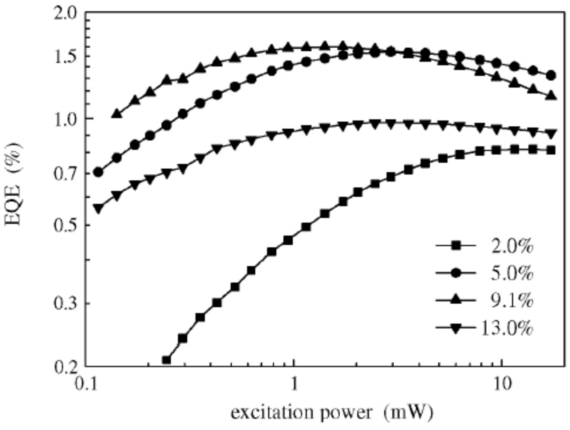
Rare-earth doped glasses are a natural candidate for two and three photon upconversion

Efficiency strongly depends on host glass (phonons), doping levels and excitation intensity, but are still low (<2%).

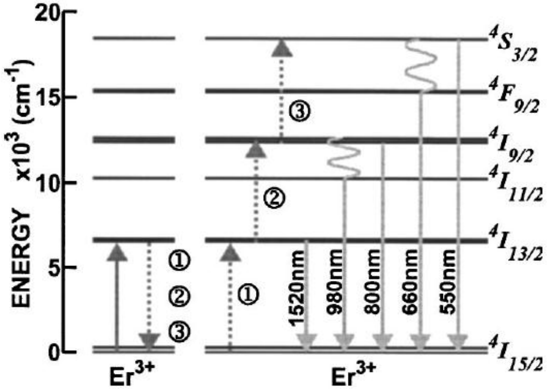
Thulium^{3+}







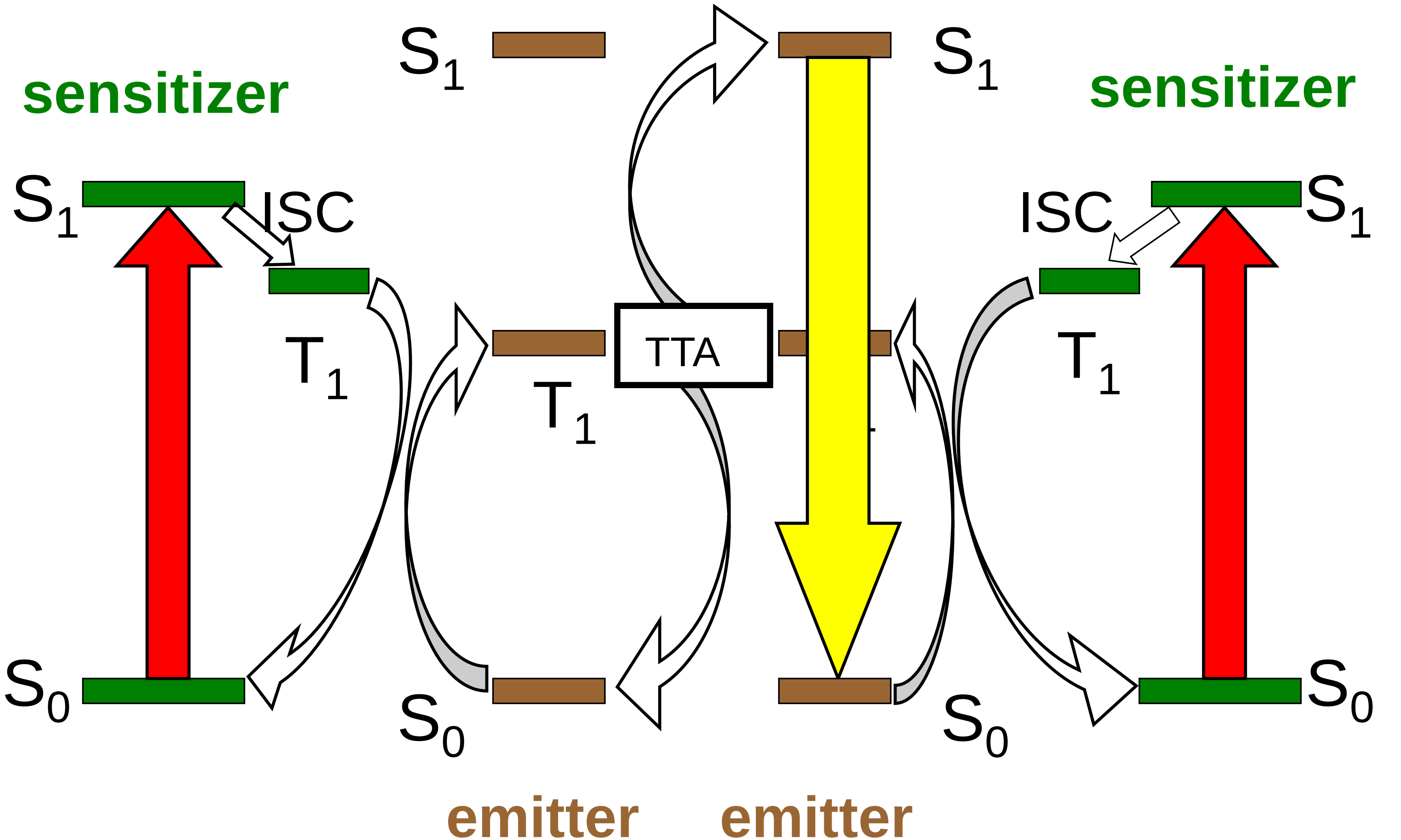
Erbium^{3+}



Henke et al., Proc. SPIE 7411 (2009)

Photon upconversion

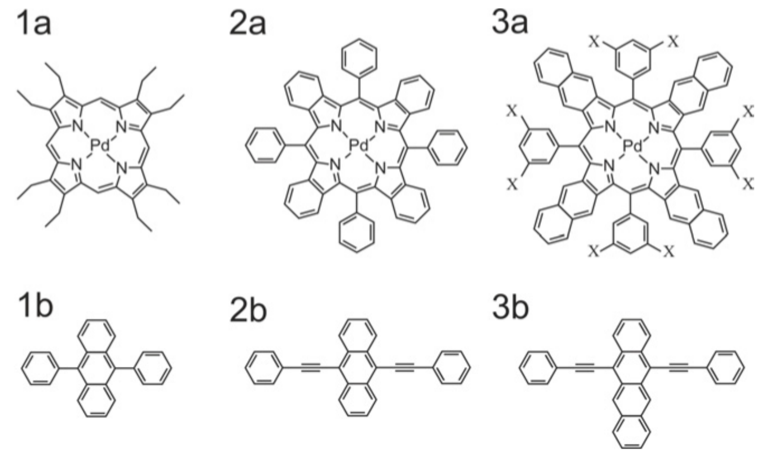
Triplet-triplet annihilation

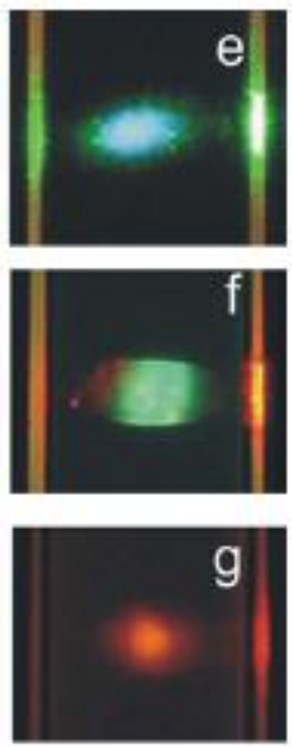


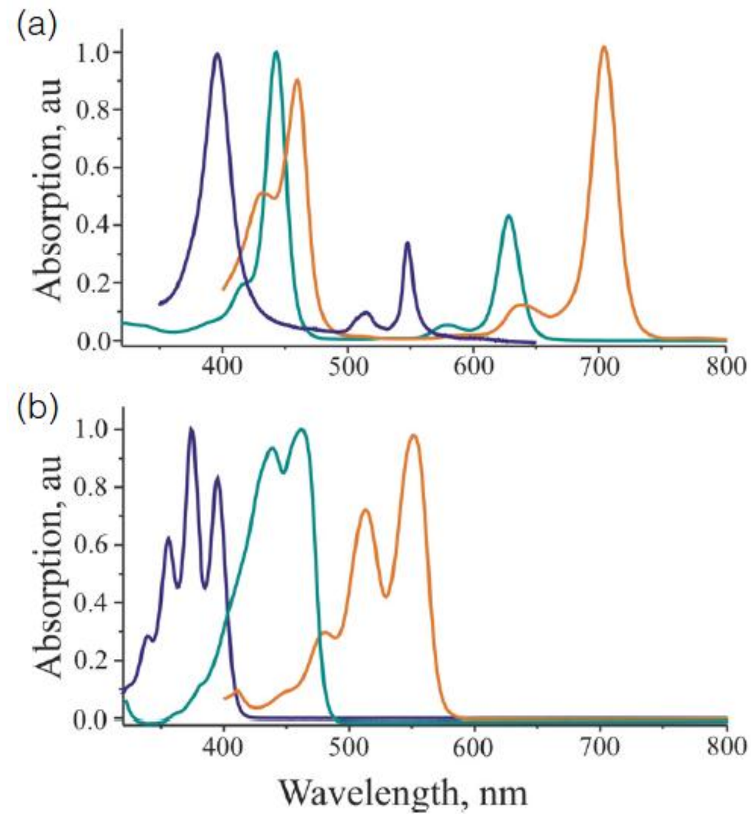
Photon upconversion

Triplet-triplet annihilation is practical only upon availability of dyes, mostly in the visible and very near IR

Current efficiencies are at the level of a few percent, stability issues notwithstanding.



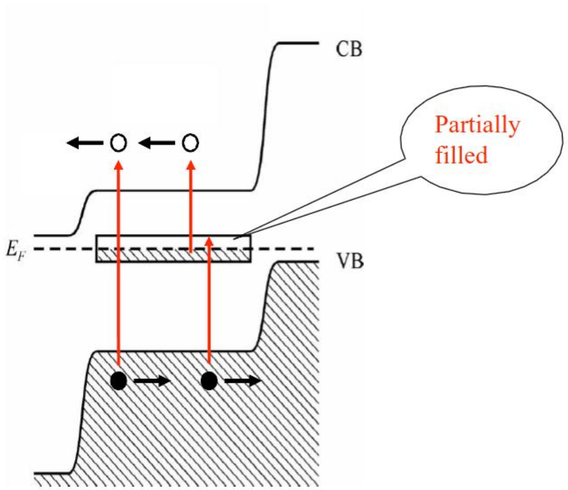


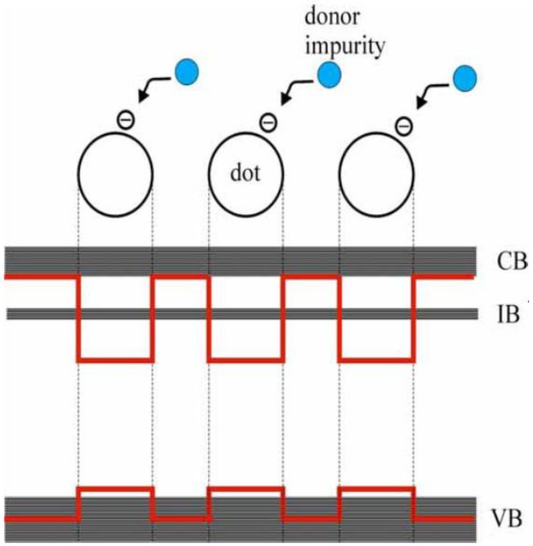


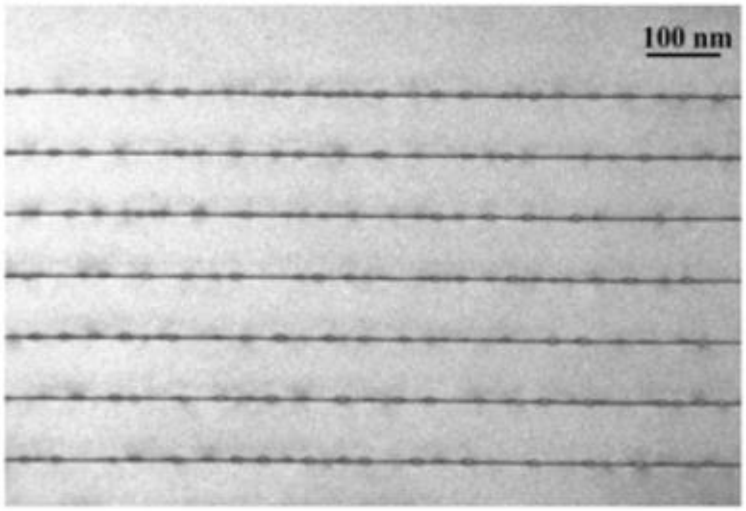
Photon upconversion

Digression: Intermediate band cells

Analogous to upconversion, only now it's the electron that gets two 'kicks'.
Problem: need to harvest carriers from intermediate band while avoiding recombination

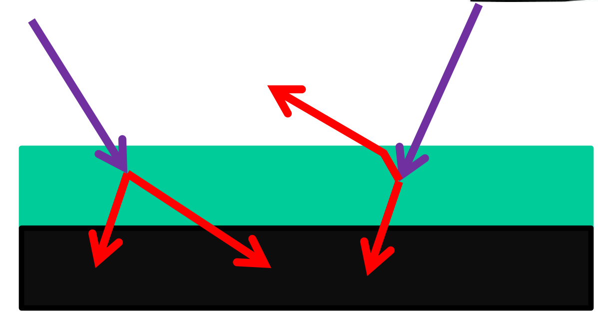




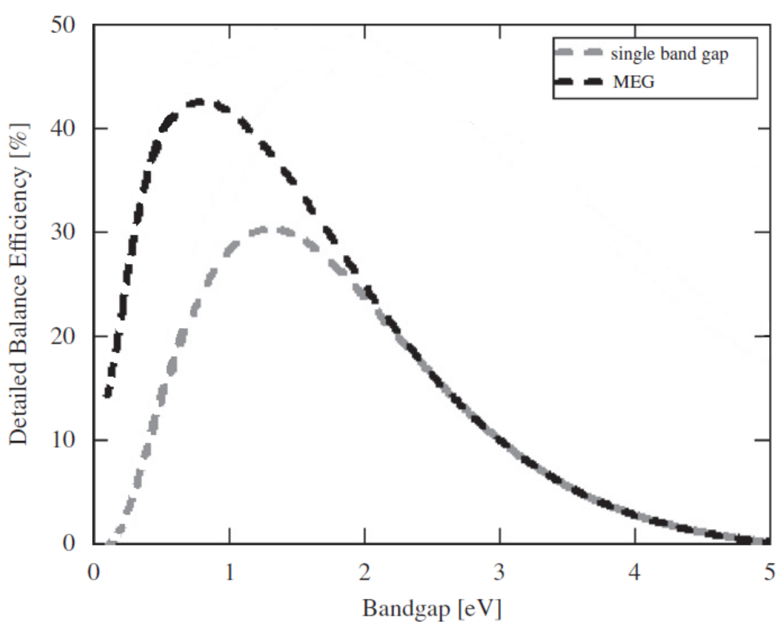


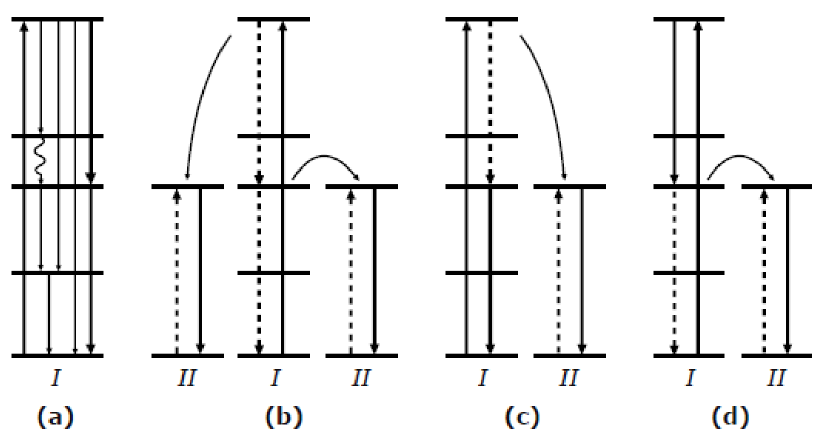
"Harder": quantum cutting

Splitting one high-energy photon into two low-energy photons potentially improves cell performance by reducing heat dissipation losses



Need ~115% yield to overcome radiation loss

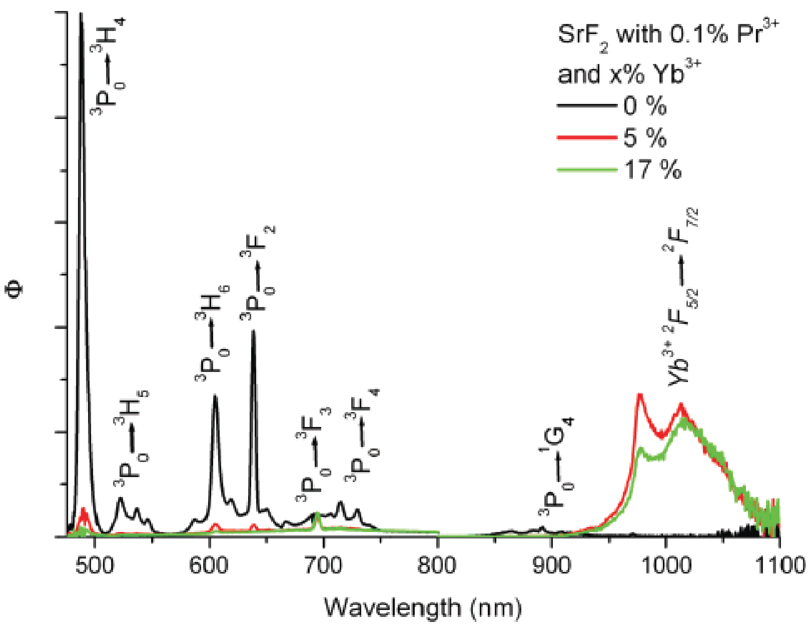


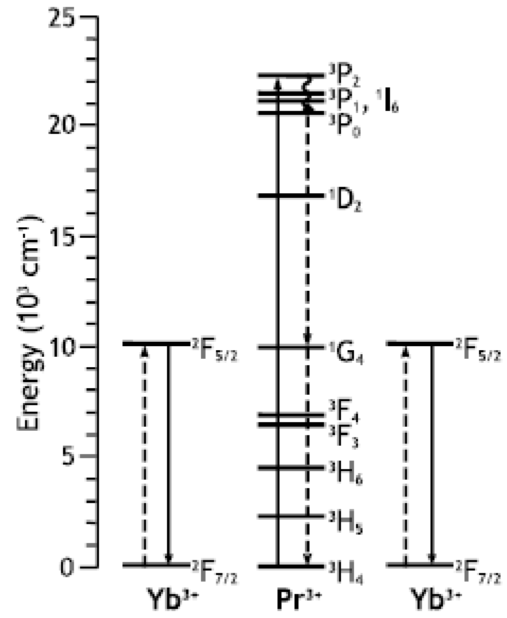


Quantum cutting

Only practical system realized exhibiting quantum efficiencies > 115% is composed of glasses doped with rare-earth ion pairs (Near UV -> 2 NIR)

~140% efficiency for 380nm absorption



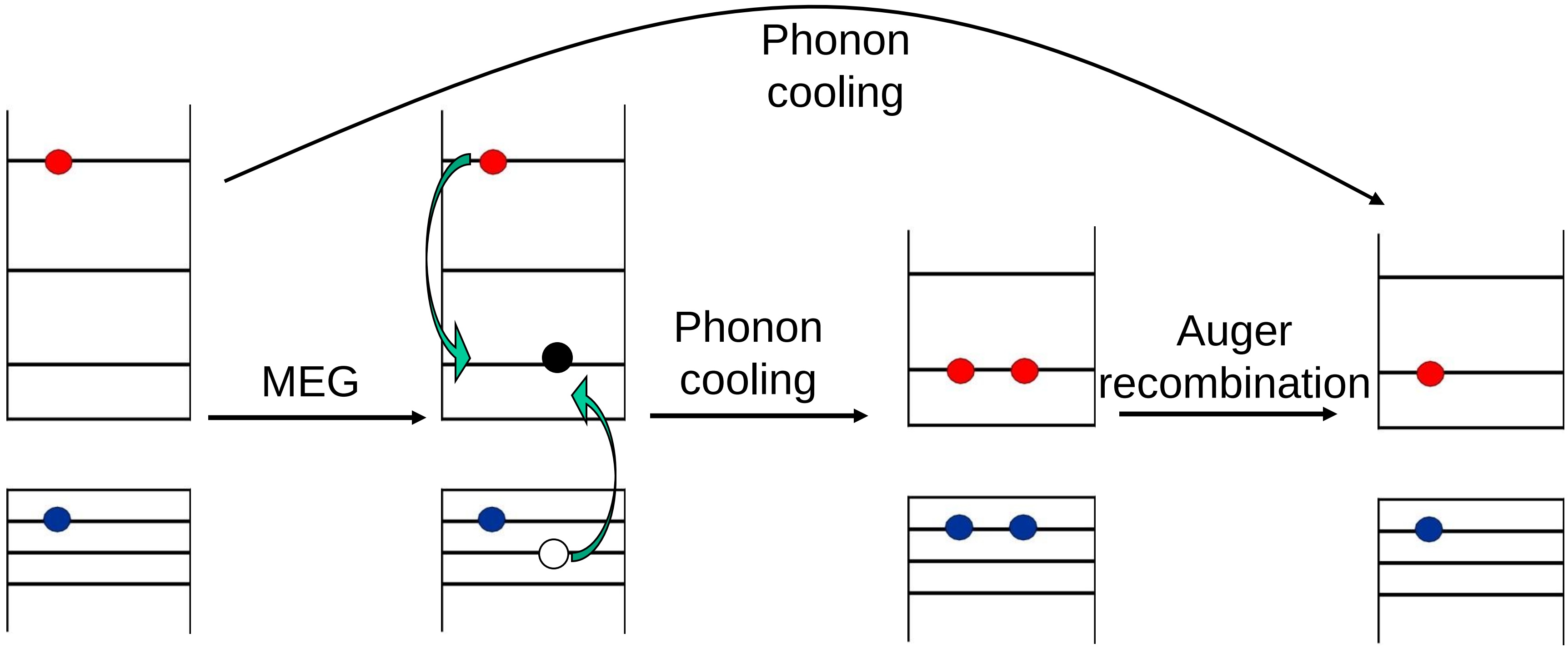


B. M. van der Ende, L. Aarts, A. Meijerink, Adv. Materials, 21, 3073 (2009).

Quantum cutting

Digression: Multiple exciton generation (MEG)

Impact ionization can lead to the generation of two excitons from one high energy photon. In nanocrystals this is arguably more efficient than in bulk.

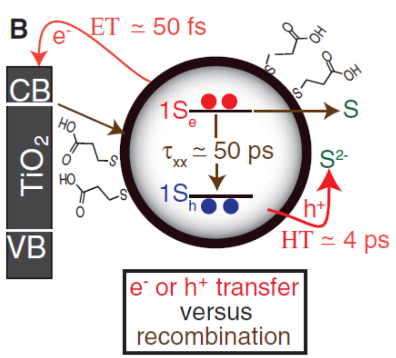


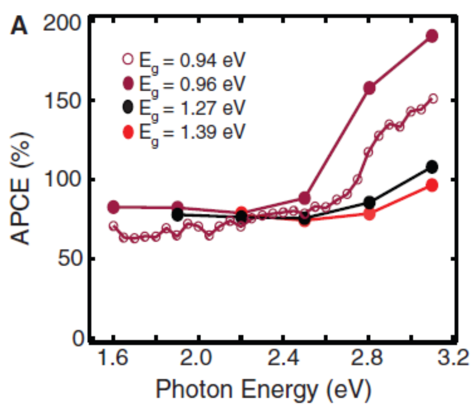
Quantum cutting

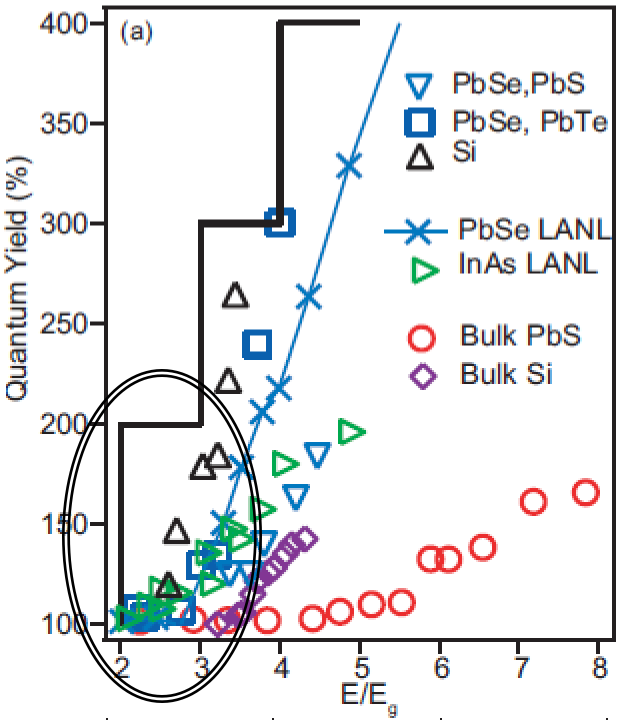
Multiple exciton generation (MEG)

Initial hopes for high yield MEG in quantum dots proved false due to experimental artifacts …

The effect is real, though





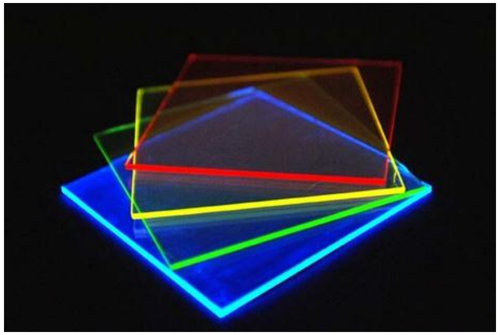


Perhaps in other systems (pentacene pairs, CNTs) …

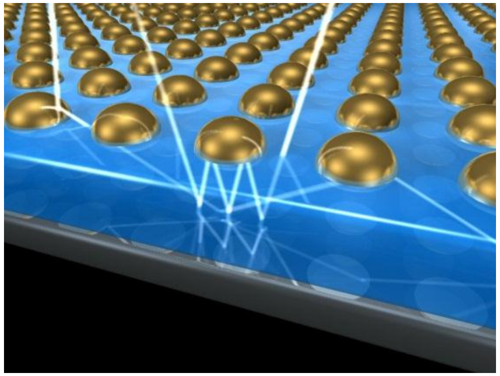
Sambur et al., Science 330, 63 (2010) ; Beard & Ellingston, Laser & Photon. Rev. 2, 377 (2008)

New (revisited) concepts

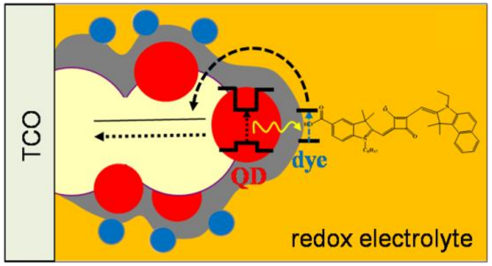
Luminescent solar concentrators
(Weber & Lambe, JPA, 1976 ;
Resifeld & Neuman, Nature 1978)



Plasmonic solar cells
(Gersten & Nitzan, JCP, 1981 ;
Brusilovsky et al, CPL 1988)

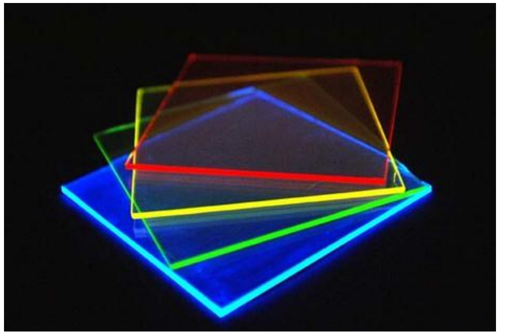


FRET-based solar cells
(Basko et al, EPJ B, 1999)

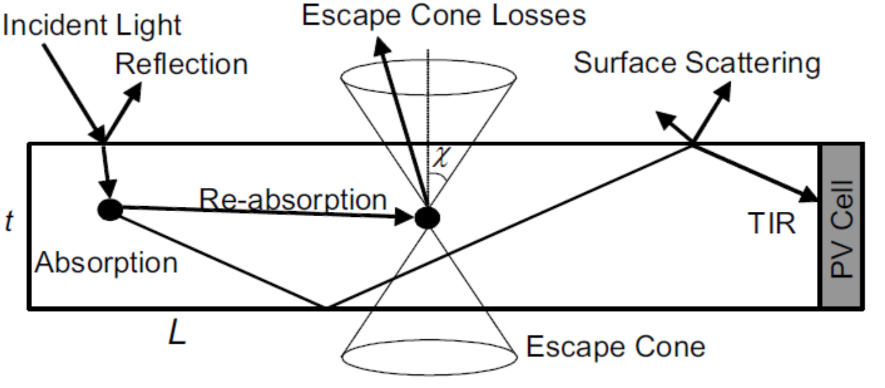


Luminescent solar concentrators

Light concentration by trapping fluorescent emission in a waveguide. Best cell 7.1%.



Advantages:
- Cheap
- Light concentration
- Simple color separation



Issues:
- Limited concentration (reabsorption)
- Radiative losses (non-directional emission)
- Durability

Van Sark et al., Opt. Express 16, 21773 (2008).

Luminescent solar concentrators

Reabsorption

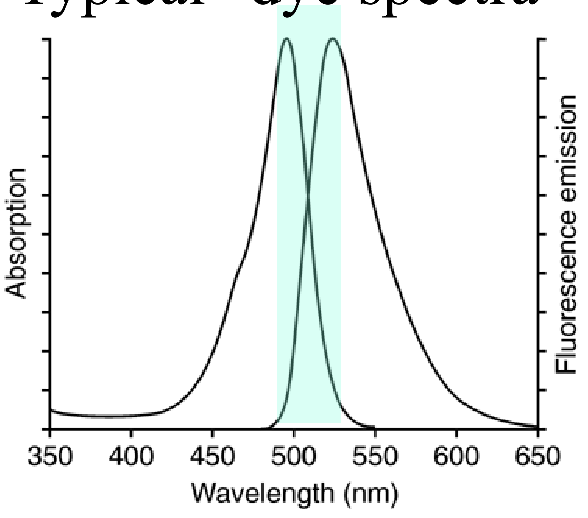
Significant loss if QY is below unity

Major loss channel even if QY is unity, due to loss cone

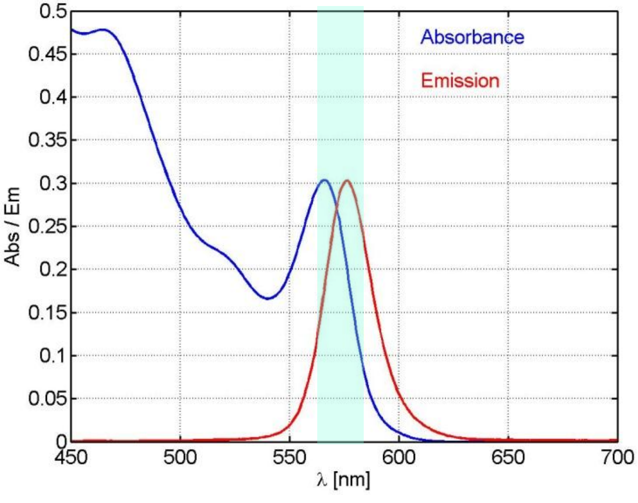
Can be mitigated by designing fluorophores with larger Stokes shift

Practically limits concentration ratios to ~10.

"Typical" dye spectra



"Typical" QD spectra

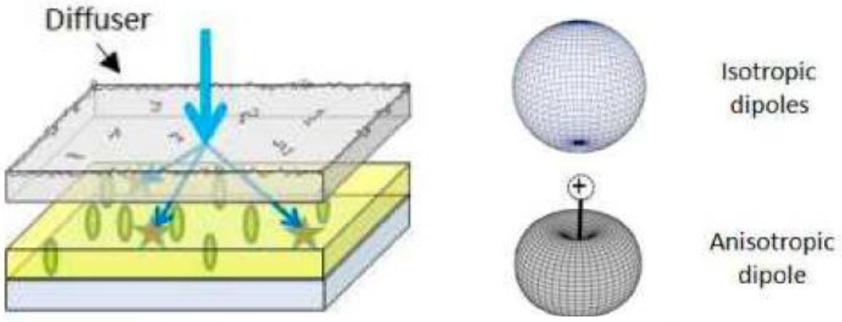


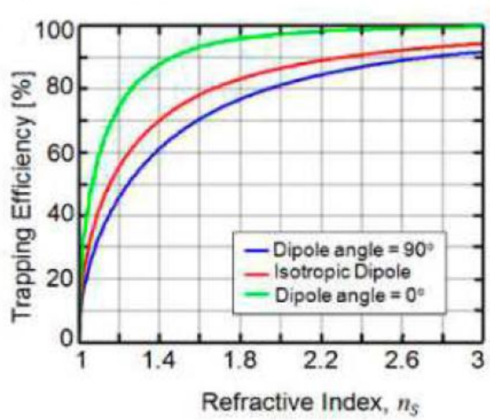
Luminescent solar concentrators

Loss cone

Cone angle can be reduced by higher refractive index substrate (but need AR)

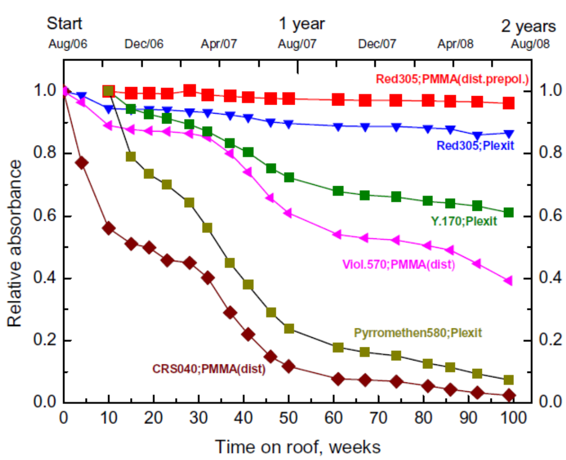
Loss probability can be reduced by orienting emitter dipole moments (e.g. in LC)





Photostability

Is a big issue since dyes actually have to emit…

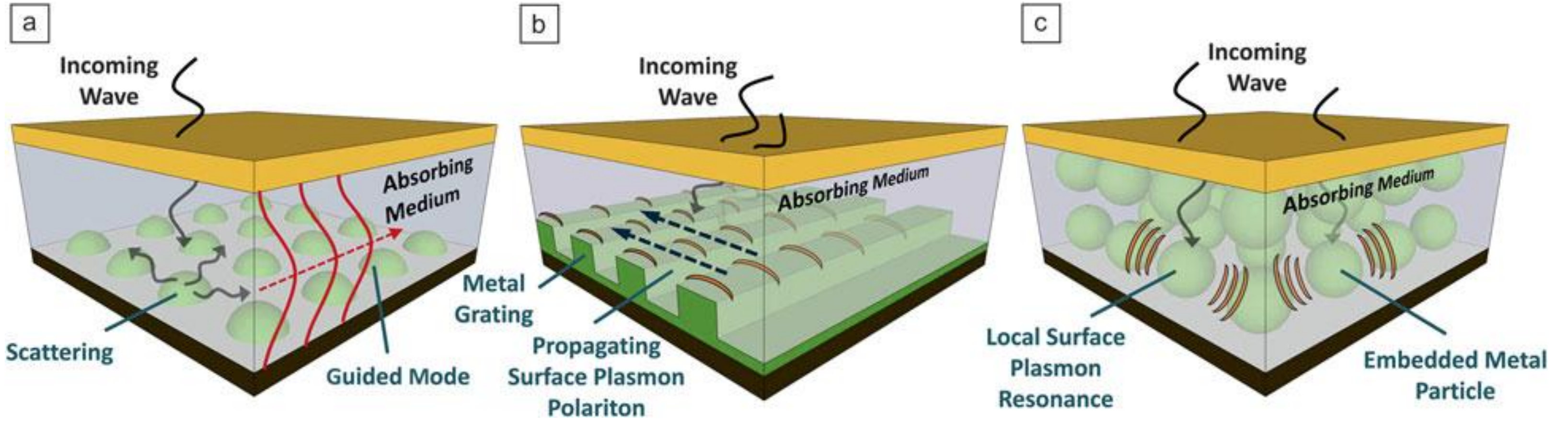


Mulder et al., Opt. Express 18, A79 (2010).

Plasmonic solar cells

Use very thin film absorbers but maintain high absorption using <u>resonant scattering</u> in metal nanostructures

Caveat: wherever there's resonant scattering, there's also dissipation



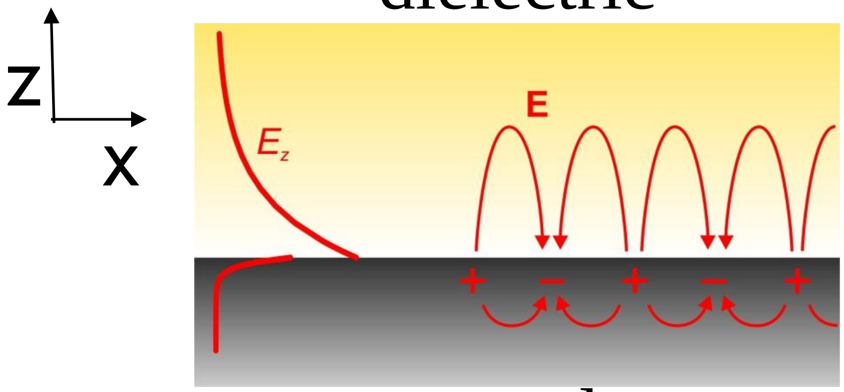
Plasmonic solar cells

Plasmons are collective electron (plasma) oscillations, often coupled to an electromagnetic field.

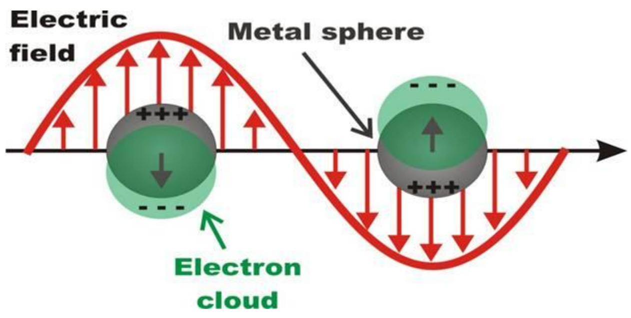
Two plasmon “flavors”

Propagating surface plasmons | Localized surface plasmons

dielectric



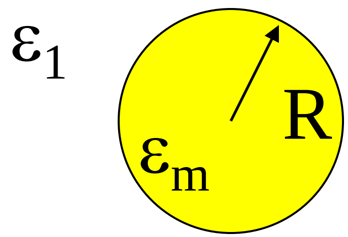
metal

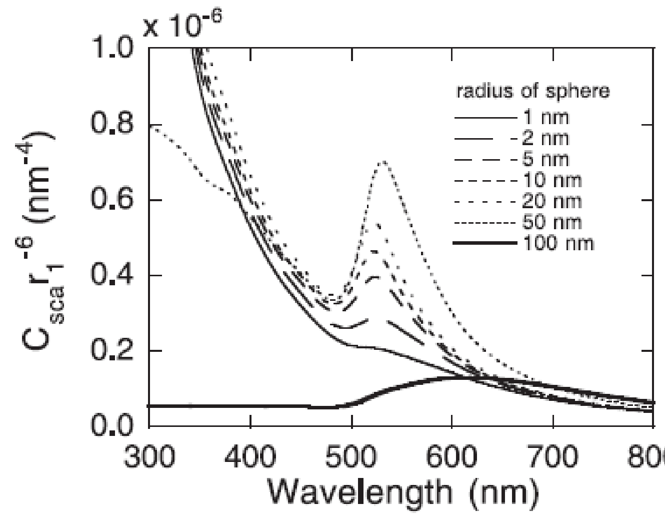


Plasmonic solar cells

Plasmon resonance of a metallic sphere

Electrostatic solution
(R<<λ):
Sphere is a point dipole
with polarizability α



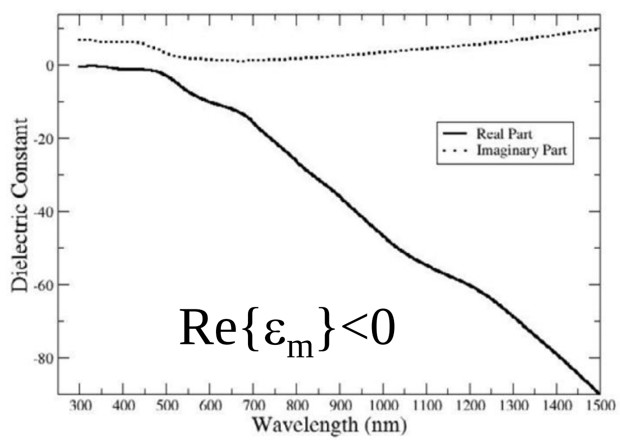


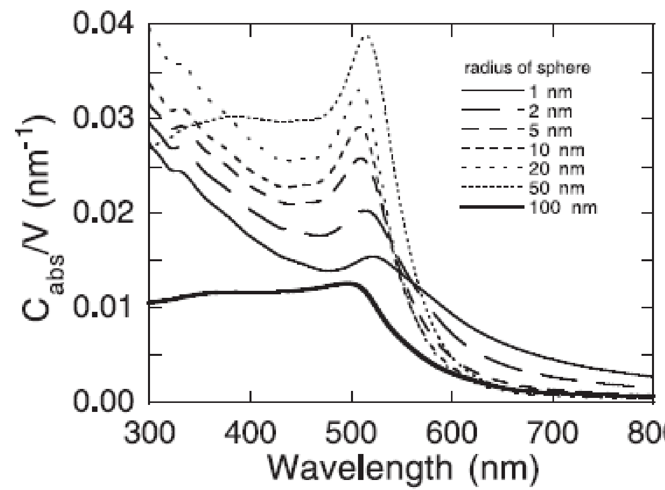
$$\alpha = 4\pi R^3 \frac{\varepsilon_m - \varepsilon_1}{\varepsilon_m + 2\varepsilon_1} \longrightarrow$$

Scattering ~ Re{α^2}

Absorption ~ Im{α}

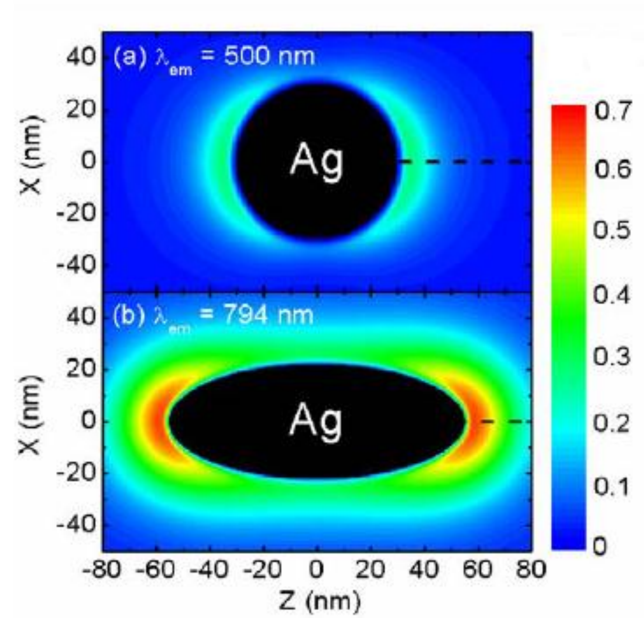
Close to 0 at resonance





Plasmonic solar cells

At the appropriate frequencies scattering is resonantly enhanced

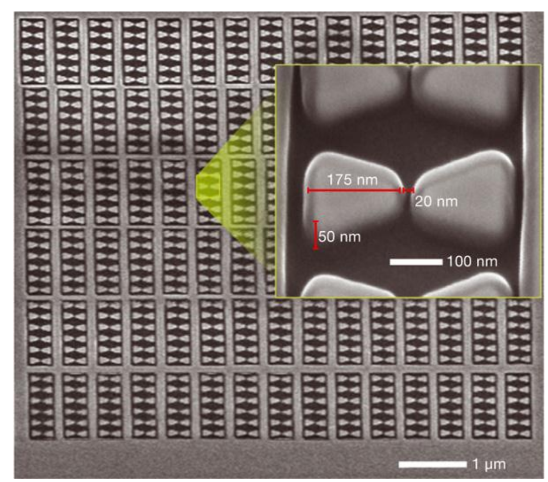


Plasmon excitation also implies nano-focusing of electric fields near particle surfaces

⇓

Optical absorption and emission in surrounding materials is enhanced

Structured antennas further enhance fields

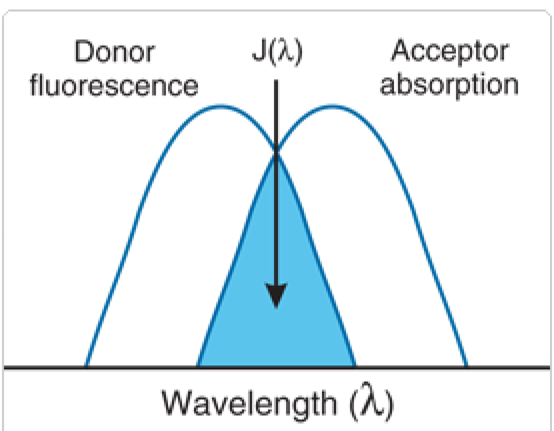


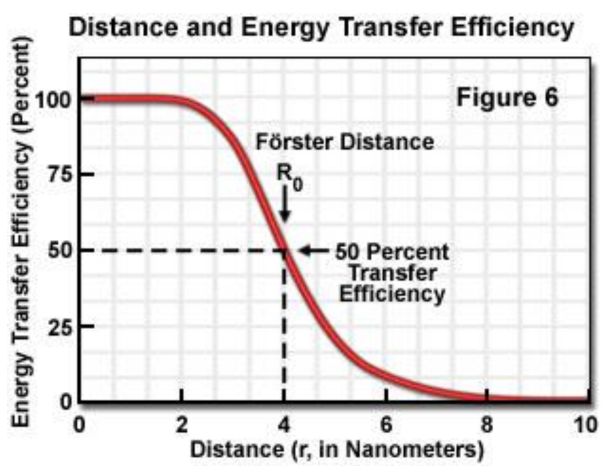
FRET based cells

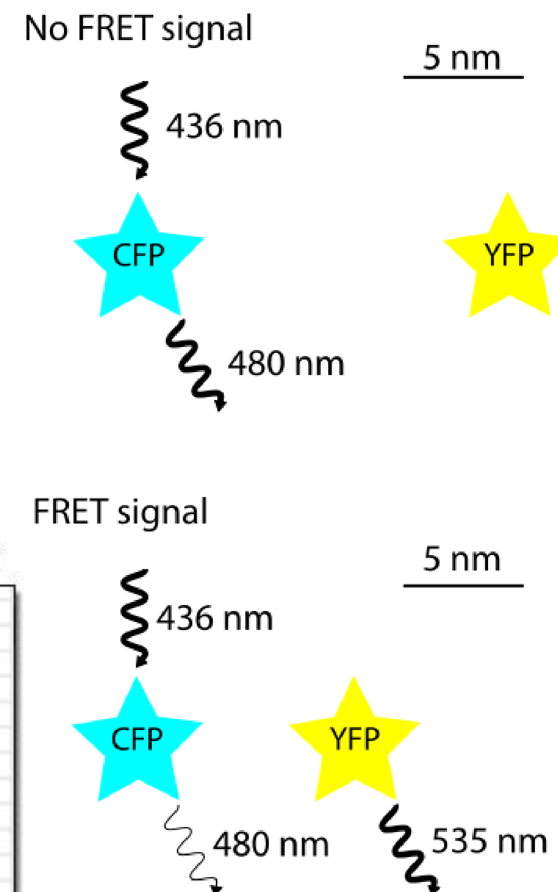
FRET is a nonradiative dipole-dipole interaction (exchange of a “virtual photon”) between a donor and an acceptor

Short range:
(R_0 is nm’s)

$$P \propto \frac{1}{1 + (r/R_0)^6}$$



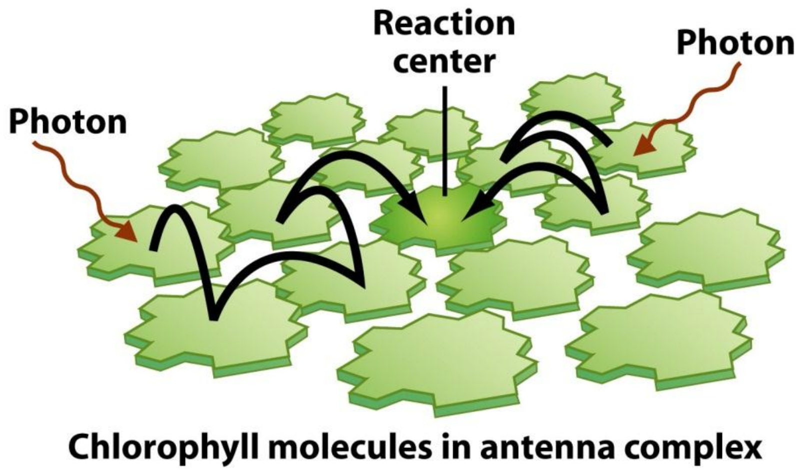




FRET based cells

In leaves, light collection occurs in a large 'antenna' while the photochemical reaction occurs in a well defined position

Energy flows from the antenna to the reaction center via FRET



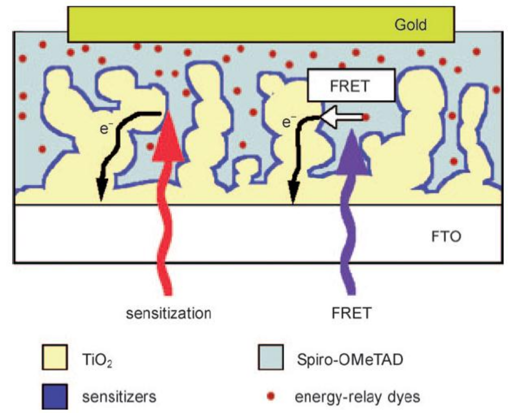
FRET based cells

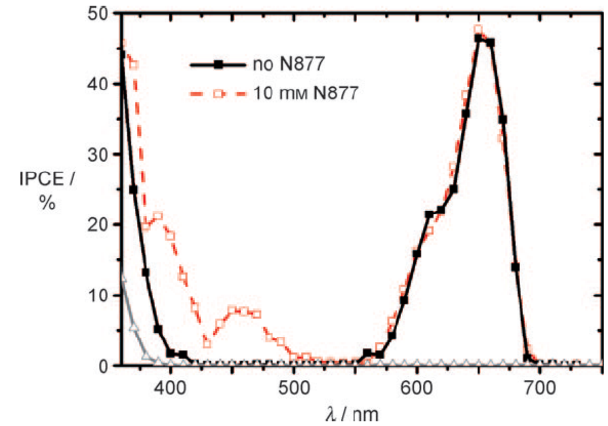
RET enables coupling of different chromophores.

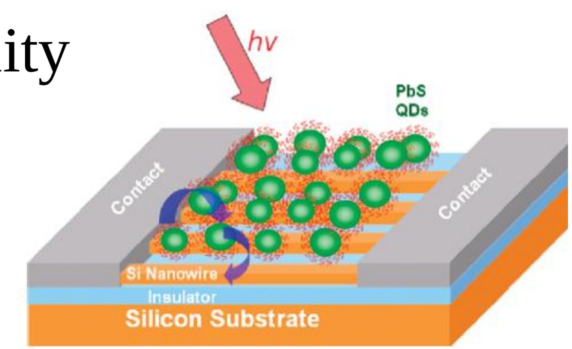
- Use of lower QY systems as intermediaries
- Spectral multiplexing using multiple chromophores
- Improved donor stability

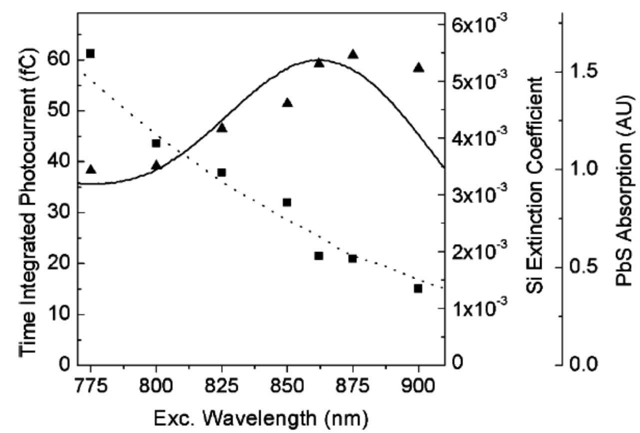
But needs:

- Proximity





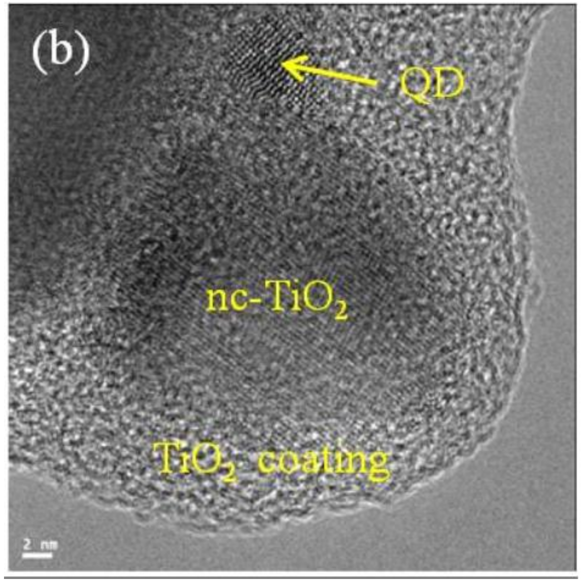




J.-H. Yum et al., Angew. Chem. Int. Ed. 48, 9277 (2009) ; S. Lu et al., Nano Lett. 9, 4548 (2009)

FRET based cells

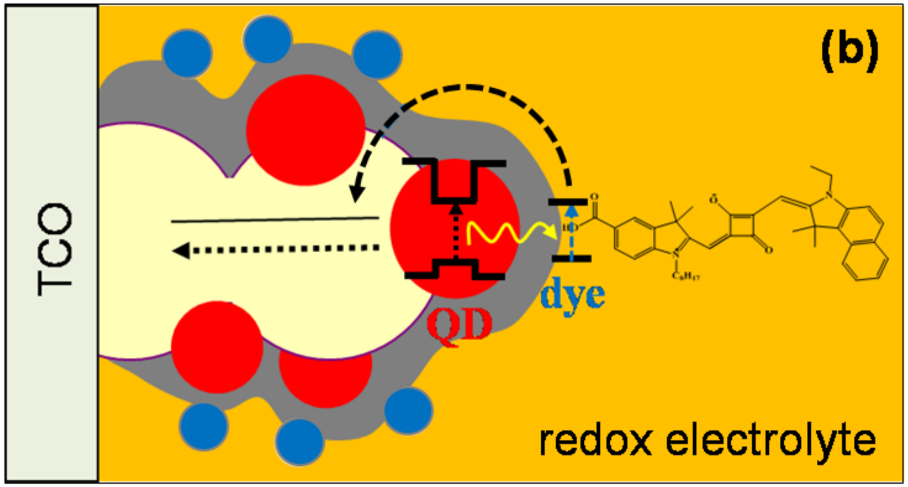
Example: QD donors broaden the absorption spectrum of DSSCs while being protected from the corrosive electrolyte by a thin inorganic layer.



Absorption by QDs

Forster energy transfer to dye molecules

Charge separation by dye molecules



Buhbut, Izhakov, Oron, Zaban et al., ACS Nano 4, 1293 (2010).

Conclusions

• Light management is a reality in working cells. Many routes to improve simple components such as AR coatings or scattering layers.

• Still no promising route for beating Shockley-Queisser by either upconversion or quantum cutting

• New materials open up new possibities

• So does revisiting old ideas with new fabrication technologies.

Thank you for your attention!